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GREEN POWER FOR AFRICA: OVERCOMING THE MAIN CONSTRAINTS

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Planning for Electrification: On- and Off-Grid Considerations in Sub-Saharan Africa

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Abstract Energy poverty, in particular, the lack of access to electricity, is a chronic impediment to sustainable development in sub-Saharan Africa, affecting over one billion people. Recently, electrification efforts have bifurcated into two pathways: grid extension/enhancement and off-grid. Expanding and enhancing the existing national grid is the *de facto* approach, but is struggling to keep up with growing populations and demand in many countries. Off-grid solutions such as solar home systems and mini-grids are seen as a way to ‘leap frog’ the national grid, but face distribution, affordability, and regulatory challenges. This article explores each electrification pathway through the lens of a traditional power system planner. This perspective shows that implicit planning assumptions about cost recovery, procurement, reliability requirements, economic benefit, what entities are involved, and the role of renewable energy require re-visiting and re-invention in the sub-Saharan African context.

Keywords: renewable energy, off-grid, power system planning, energy poverty, grid extension, products as a service, electrification, mini-grids, micro-grids, probabilistic connection.

1 Introduction

The electrification rate of households in sub-Saharan Africa (SSA) is presently at 37 per cent (IEA and World Bank 2017). Those with electricity access are often challenged by an unreliable, unavailable, and inadequate supply (Billinton and Jonnavithula 1996). Electricity underpins many broader development goals, and its positive association with education, health, and economic prosperity has been noted in existing literature (IEA and World Bank 2017; Franco *et al.* 2017; Socvacool and Ryan 2016; White *et al.* 2008). With this impetus, governments in countries throughout SAA have moved to increase electricity access (Bhattacharyya 2013). To this end, electricity supply planning plays a crucial role. However, traditional assumptions and notions of planning as might be followed in countries with mature power systems with universal access are challenged in the context of

SSA (Trotter, McManus and Maconachie 2017; Eberhard and Gratwick 2011; Malgas and Eberhard 2011).

A salient difference in power system planning in SSA is the notion that electricity supply can be provided not only by extension of the national grid, but also by off-grid systems. Economically viable, sustainable, and scalable off-grid electricity access – primarily by small-scale solar systems, solar lanterns, and mini-grids – has only recently become possible. It is disruptive to traditional planning processes, and may hold lessons in jurisdictions where these habits hold sway.

The literature on the subject has explored comparisons between on- and off-grid electrification from technical (Trotter *et al.* 2017; Szabó *et al.* 2011), economic, and development perspectives (Wamukonya and Davis 2001). This article focuses on electrification through the lens of a power system planner to probe how the underlying assumptions to traditional electricity supply planning tend not to be satisfied in SSA, and hence the process must be modified. It is suggested that more robust and flexible planning processes will be emerging from this context due to tight economic constraints, the need to address widely different levels of demand as well as different requirements of service quality, and the growing experience with disruptive technologies like cheaper energy storage.

The remainder of this article is arranged as follows. Section 2 provides a brief overview of historical experiences in electrification providing valuable lessons for SSA. Section 3 discusses the state of electricity access in SSA, considering on- and off-grid populations. Basic concepts of electricity supply planning are reviewed in Section 4. Sections 5 and 6 discuss how notions of traditional electricity supply planning are challenged in the context of on- and off-grid electrification in SSA. Conclusions and an outlook are provided in Section 7.

2 Historical experience in electrification

Universal access has not been a spontaneous event in the many countries that have achieved it. On the contrary, a number of conditions needed to be satisfied, among which are long-term dedicated private and public investment, access to cheap and patient capital, the ability to pay for electricity by wide segments of society, and an unclouded political vision and follow-up. This section compares the electrification-by-grid-extension experience in different countries, highlighting those factors and showing possible implications for the African context.

The United States (US) was among the early leaders in the development and implementation of electricity (Wamukonya and Davis 2001). However, access to electricity in rural areas notably lagged behind many other countries. Electrification began in urban centres serving a clientele willing and able to pay high premiums for an electricity service. Electricity providers made a concerted effort to install large generators, enlist more customers, and lower the cost of electricity production

by reaching higher-capacity factors.¹ By being able to run their large generating stations fully for as much of the time as possible, they improved the returns to their investment.

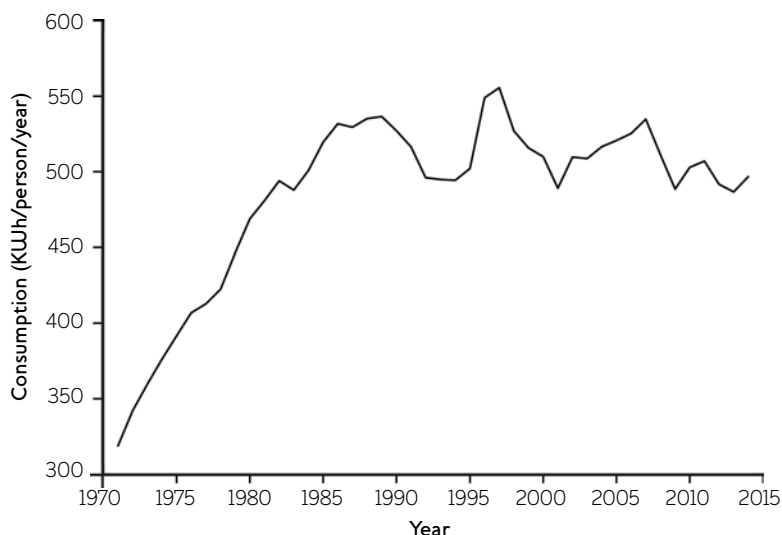
Electrification expanded quickly in urban areas, but rural areas lagged behind. In 1935, just 10 per cent of farms in the US had grid access. The reasons for the low rate are similar to those identified today in countries that struggle with electrification. As summarised in a 1934 report by the Mississippi Valley Committee, the reasons for low rural electrification include ‘... the lack of interest by operating companies in rural electrification... high cost of construction... restrictions covering rural line extension... and high costs’ (Beal 1940). In short, the privately owned electric utilities could generate more profit by serving urban rather than rural customers.

It took government intervention to make electricity accessible to the rural population. The creation of the Rural Electrification Administration and the passing of the Rural Electrification Act in 1936 provided the catalyst for rapid rural electrification (Hughes 1983). Access to finance at low rates and high maturities and good communication with rural populations caused rural electrification rates to rise to 25 per cent by 1940, and to virtually 100 per cent by the 1950s. In less than a generation, the rural electrification of the US was complete.

China – a country of over one billion people and an expansive geography – has nearly universal access to electricity. This includes rural areas, where half of the population live, thanks to the use of community and municipal management. This is in stark contrast to India, the other Asian giant, whose rural electrification rate had reached only 70 per cent by 2014. As in the US experience, rural electrification in China lagged behind urban (Bhattacharyya 2013). The rural electrification rate was 61 per cent in 1978. By the end of the 1980s, the electrification rate reached 80 per cent, and by the turn of the millennium, it was virtually 100 per cent, for a population three to five times the size of the US.

China realised rapid electrification through various government-backed programmes, including the Township Electrification Programme, which is the largest renewable energy supply programme in the world (Bhattacharyya 2013). Over the last 50 years, the organisation of the rural electrification effort has evolved. More recent success is attributed to the empowerment of local county- or village-level government by the central government to manage rural electrification. This bottom-up approach, while still governmental and not free-market-led, is unique and could be adopted by other countries. The programme leveraged locally available energy sources, including small-scale hydro, to build out localised grids, which were eventually connected to the national grid. While this allowed access to rapidly increase, the localised grids were often poorly designed, not standardised, and used low-quality components. This underinvestment in the grid led to high system

Figure 1 Per capita electricity consumption in sub-Saharan Africa



Source World Bank Open Data (n.d.).

losses, low reliability, and need for replacement once connected to the national grid. However, even a lower quality electricity supply provided the conditions for the economic improvement and electricity demand growth necessary to justify and sustainably finance a grid connection, qualifying it as the successful pursuit of a socioeconomic electrification goal (Bhattacharyya 2013).

The experiences of electrification of the US and China hence show that a heavy involvement of the state was required, jointly with access to patient capital, the existence of an urban critical mass that could pay the actual cost of the service and, in the Chinese case, a bottom-up approach adapting energy supply to the local energy sources and to the characteristics of local demand.

3 Present state of electricity supply in sub-Saharan Africa

In many African nations, the demand for electricity has outpaced centralised infrastructure growth, in terms of generation sources built, transmission lines strengthened, and distribution systems extended (Practical Action 2016). The exponential tripling of population from 1970 to 2010 gives a rate to be matched in some sense by electricity infrastructure. However, population does not equate to an economically viable demand for electricity.

3.1 National grids

The total generation supply in SSA, excluding South Africa, is approximately 100,000MW in a region with almost one billion people. This supply is on a par with Spain, a country whose population is less than 50 million. Per capita electricity consumption in SSA shows a similar gap and it has not improved since the mid-1980s, as seen in Figure 1.

Power systems in developing nations tend to have a small number of generators covering a large area. In SSA, excluding South Africa, nation states have total generation capacities ranging from 0.4GW to 8GW of capacity (Macro Economy Meter 2013). For their populations, the capacity is on the order of 10–100 watts per capita, versus 500–5,000 watts per capita in industrialised countries (Sanjay 2015). Connections between neighbouring countries are not strong, making many countries electrical islands. This isolation, as well as the small number of power plants, long distances, and heavy reliance on hydropower (Macro Economy Meter 2013; Sanjay 2015) or imported fuels² make SSA power systems particularly vulnerable.

3.2 Off-grid

Off-grid solutions can address some of the vulnerabilities highlighted above. Furthermore, they can directly target the rural population constituting the majority of some 600 million people who have no access to the electrical grid in SSA (IEA and World Bank 2017). In rural areas, the lack of legacy electrical infrastructure has allowed electricity services to be re-imagined in the form of off-grid renewable energy electricity solutions provided by for-profit companies and energy entrepreneurs, in some cases with the support of donor agencies (Birol 2015; Byrne *et al.* 2014). Technological improvements have enabled these new business models. In particular, the steady and comparably drastic drop in solar panel, inverter, and LED technology costs due to industry experience has lowered barriers to decentralised provision of electricity (IEA and World Bank 2017; IEA 2005; Birol 2015; Energy Sector Management Assistance Program 2015; Louie *et al.* 2015; Bloomberg New Energy Finance and Lighting Global 2016; Mandelli *et al.* 2016).

New off-grid systems often provide limited amounts of power. For example, solar lanterns can only provide light. Solar home systems typically consist of a solar panel with a capacity from 5W to 300W – a lead-acid or lithium ion battery in a ruggedised case with an integrated LED light and/or ports for charging mobile phones. Larger-capacity solar home systems are capable of powering small appliances such as televisions and fans (Bloomberg New Energy Finance and Lighting Global 2016). The small size of these systems has not precluded widespread adoption, with over 40 million solar lanterns and solar home systems deployed (Bloomberg New Energy Finance and Lighting Global 2016) and a market exceeding US\$500 million in 2015 (Global Leap 2016).

Larger scale off-grid systems, referred to as ‘mini-grids’ or ‘micro-grids’, provide higher-capacity access to rural customers, and are approaching or even exceeding the quality of service of grid-connected electricity (Louie *et al.* 2015). Hybrid power systems based on diesel generators, photovoltaic panels, and batteries are being developed by for-profit companies which can attract sufficient capital to offer power contracts to commercial customers with a lower cost of energy, higher reliability, and greater convenience. These systems require specialised planning to be economically viable and sustainable, and are still following a technology and system integration experience curve towards lower costs and better performance.

4 Concepts for traditional electricity supply planning

This section introduces some key concepts related to the activity of electricity supply planning, which will be necessary to assess the two potential electrification pathways for SSA. Electricity supply planning differs from day-to-day electricity supply operations by the timescales considered, its goals, and the tools used. Electricity supply operation is a real- or near-real-time activity focused on maintaining reliability at the lowest cost possible. On the other hand, planning horizons are many years in the future and decisions are based on uncertain projections of conditions, but the goals remain focused on achieving a given reliability at least cost (Conejo *et al.* 2016).

Successful planning outcomes are reached through a set of activities: (1) estimating demand and demand growth, (2) selecting generation technologies, (3) planning operations, (4) designing transmission and distribution networks, and (5) ensuring an enabling environment for plan implementation (Trotter *et al.* 2017). Sound planning decisions balance initial costs with long-term expectations, and the needs of one user against another.

We now introduce several aspects relevant for the two potential electrification pathways for SSA from the perspective of a planner; namely: the actors engaged in planning activities; the fulfilment of economic and social goals; the quality of service; and the implications of increased penetration of renewable energy sources.

4.1 Actors

Electricity supply planning has traditionally been the purview of utilities – both government and independently owned –, regulatory entities and at a high level, government ministries or agencies.

Independent power producers also plan and announce their projects, but usually in the context of a national pace set by government ministries and the regulator (Eberhard and Gratwick 2011; Malgas and Eberhard 2011; Global Leap 2016). It is the responsibility of the wider power sector, which includes technicians, standards reinforcement branches of the regulator, and regulated utility companies to cooperate with the plans set. This is part of the aforementioned activity of ensuring and enabling an appropriate environment.

4.2 Economic and social goals

The difference between economic, socioeconomic, and social goals can be usefully articulated to support planning activity, including the selection of appropriate technology and policy, as hypothesised in Conejo *et al.* (2016).

A purely economic goal is met via a traditional assessment of rates of return. In this case, the means of cost recovery is directly from users, whose ability to pay can justify the investment. Economic returns can be maximised when the capacity factor of generation assets is high.

A socioeconomic goal has overall positive social welfare (in the economic sense), but requires the careful design of cross-subsidies. In this case, it is not the particular customer, but the collection of all customers who must offer viable cost recovery.

Finally, a social electrification goal acknowledges the environmental security and health benefits that may result from access to electricity, as a means of poverty alleviation, and does not specify a direct payback. In this case, a trade-off analysis of these benefits against other options contending for support from donors, a community, or a nation state budget is warranted. Once an expected means of cost recovery is identified, a planner can consider technologies that are appropriate for the expected financing, and for the quality of electricity access needed.

4.3 Quality of service

The service experienced by a consumer of electricity can be measured by a number of metrics locally (Billinton and Jonnavithula 1996). These refer to both quantity (power³ and energy⁴) and quality. In aggregate, industrial, commercial, and residential users, types in a region may consume roughly equal quantities of electricity, but with stark differences in the quality of supply tolerated. The quality of service continuum, more commonly referred to as ‘access tiers’, has different formulations, but generally considers dimensions such as technical quality, legality, and affordability (Energy Sector Management Assistance Program 2015).

Technical quality can be partly described by availability and reliability. Power system operators need to ensure that at every moment, the power consumed (inclusive of losses on the power lines) matches the power generated from some source. If there is insufficient fuel for power plants, or these are not operating due to technical faults, then energy cannot be provided to customers, and either electricity rationing or a blackout must occur (Macro Economy Meter 2013; Conejo *et al.* 2016). Similar concepts apply to off-grid systems, although at a smaller scale. A solar-powered system is limited by the power it can supply at any moment, and the energy it can supply from its storage over periods when the sun is not available.

Due to these mismatches between demand and supply, the availability of a live electrical connection expressed as a fraction of a chosen time period is often less than one. Beyond the customer level, we use several measures of system reliability, which tend not to acknowledge a specific location, but characterise the frequency and duration of interruptions across a region over a chosen time period, as well as the likelihood of demand not meeting supply at a system level, which would provoke a wider disruption. At the regulatory level, planning processes are required to result in levels of generation and transmission sufficient to make this likelihood acceptably low in the face of credible events. This provides the condition called ‘adequacy’, which is a term applied to indicate that the generation available has a suitable surplus to counteract unplanned events (Billinton 1970).

4.4 Renewables

Renewable energy has been increasingly incorporated into long-term plans due to significant cost reductions, and to subsidies and targets as part of climate change mitigation commitments. Renewables make sense from an energy planning perspective when they are low cost and improve energy security, being locally available (AfDB 2012). However, the most widespread renewable sources of wind and solar introduce new challenges for power planners. Their variability and uncontrollability mean that their contribution to meet electricity demand is uncertain. Additionally, the best renewable energy resource is not always located close to centres of demand, which requires heavy investments in transmission lines to both access and then channel the available power to locations with higher demand and price (Smith *et al.* 2010). As the proportion of wind and solar become greater, power system operations can be affected, as it becomes more difficult to balance supply and demand. Because of this, planners often request technical grid integration studies before they agree to new renewable generation plants. A limit on allowed generation development may be imposed to remain within these operational limits and the capabilities of planned extension of transmission links. Because wind and solar can be deployed in distributed form in small modular pieces, some amount of generation development may go unplanned and unmonitored.

5 The grid enhancement and extension path

The rest of this article will explore two parallel paths to electrification, indicating where planning activities in developing countries may differ, and considering the way forward. The first path is grid extension.

In theory, grid extension is the most cost-effective use of capital, especially when it pursues the connection of customers near the national grid rather than those who are more distant. On the contrary, the cost of installing a power line to a rural area might cost over US\$20,000 per kilometre. What is more, because rurality and poverty are often associated, the customers tend to purchase modest amounts of energy and the investment in the power line is recuperated slowly over many years.

Some technological improvements have tackled the high cost of grid extension to rural areas, most notably the adoption in South Africa of different standards such as Single Wire Earth Return (SWER) and blanket extension. These initiatives have been found to reduce grid extension costs to near urban levels, but this required almost a decade and necessarily provides a lower tier of access (Gaunt 2003). Even in urban areas, grid overextension, and subsequent lack of cost recovery, is already a problem.

5.1 Actors

The monopolistic and long-term character of a national grid often means that political actors manipulate planning for political gain, and this is not restricted to developing countries. However, in developing

countries, the political, regulatory, and technician actors have negatively interacted to neglect the fifth planning element of ensuring an enabling environment for implementation.

The case of Nigeria holds several examples of these challenges (Uwaifo 2005). To gain popular support, politicians demanded rapid grid extension and the creation of many small and uneconomical power plants. Regional governments also created networks that were not appropriately planned or constructed. This determined pursuit of social electrification was not backed by a considered balancing of municipal, state, or federal budget. What is more, a succession of military dictatorships resulted in over a dozen years of non-payment and non-investment in the electricity sector, stretching the vertically integrated electricity utility beyond financial viability.

Under these circumstances, unlawful practices emerged within the utility to recover additional revenue from customers. Such practices regarding collection for energy received, and for new connections, began with moonlighting employees but led to a completely separate ecosystem of installing and charging for electricity connections, often without construction and safety standards. Not only did this generate a poor customer experience and lead to a lack of trust, it also created technical challenges for those operating the existing system, now loaded with unplanned connections.

It is common for governments in developing countries to establish dedicated agencies to promote, coordinate, manage funds, train, build capacity or implement rural electrification (Bhattacharyya 2013; Smith *et al.* 2010; Government of the Republic of Zambia 2009). These agencies are generically called Rural Electrification Authorities (REAs). REAs in SSA became popular beginning in the late 1990s to mid-2000s – for example, Kenya (1997), Senegal (1998), Zambia (2003), Nigeria (2005), and Tanzania (2005) were created during this period. The purview of many REAs consists of electrification through grid extension, but increasingly (Kenya, South Africa, Nigeria) off-grid systems.

Many REAs are charged with developing Rural Electrification Master Plans (REMPs). REMPs cover a multi-year period, for example ten years, and outline strategies for achieving specific electrification targets that align with broader development goals; for example, 51 per cent electrification by the year 2030 (IEA and World Bank 2015; Tenenbaum *et al.* 2014). REMPs estimate the cost of achieving the targets, and identify technological, regulatory, and financial and economic barriers, risks, and opportunities. Priorities in terms of geography and customer types, for example schools and health facilities, are identified. Although created by the government, the budget of REAs is often supplemented by external donors, which might include foundations or other governments. REAs often oversee a Rural Electrification Fund (REF). In some countries the REA allocates REF monies on a competitive basis to for-profit organisations that do the electrification.

5.2 Quality of service

Power interruptions can occur even in grid systems with adequate generation capacity and fuel, but in SSA they are a regular experience due to actual energy shortage. In Nigeria, for example, 44 per cent of customers of the national grid received less than 2–4 hours per day and at random, giving them a probabilistic connection referred to as 'bad-grid' in literature (AllOn 2016). In Malawi, planned load-shedding is turning into emergency load-shedding as river levels drop to unprecedented lows (Sanjay 2015).

In addition to fuel shortages, SSA systems suffer high rates of transmission and distribution losses, up to 20 per cent or more, with a large share of these attributable to theft (Smith 2004). As a result of poor reliability, self-generation by businesses in SSA is around 10 per cent, with some countries reaching 25 per cent and in the Nigerian case 60 per cent (Foster and Steinbuks 2009; GIZ 2015). These conditions lead to even worse service and accessibility due to degrading utility and customer equipment (Coney 1996).

In this setting, the first planning activity of electricity demand estimation and its growth is made more difficult. Some demand is physically present but not metered or distinguishable from losses due to energy theft. Where load-shedding occurs, the so-called suppressed demand is uncertain, as it is based on experiments (Godfrey, Quarshie and Robiou 1996) or proxies such as diesel-generating set purchase (AllOn 2016). Planning infrastructure to target even the estimated quantity of suppressed demand and its growth is difficult, as commercial customers that have left the grid may not wish to come back, due to low quality of supply. Where distribution grids are in especially poor repair, demand for grid electricity may even go down.

5.3 Economic and social goals

In some countries, a history of aggressive electrification targets coupled with successive sociopolitical shocks have eroded or eliminated fundamental business and technical foundations of the power sector. A functioning power sector depends on several key relationships and assumptions: payment is reliably collected from customers who find the distribution company a trustworthy and cheap alternative to home generation, distribution companies invest to maintain and upgrade their equipment while paying for energy taken from the system, the owners of generators receive payments to pay for their capital and operating costs, and the transmission owners and system operator also invest to provide all parties with a reliable connection.

In struggling power sectors (Africa, South America, Eastern Europe) it is common to find economically disadvantaged customers who receive a low quality of service, and are also extorted by current or former distribution company employees (Gratwick and Eberhard 2008). The unavailability of electricity due to rationing and blackouts leads to customer dissatisfaction and non-payment of bills (Winther 2012), as

well as significant diversion of revenue from bills that are actually paid away from maintenance.

While the installation of automatic or remote meters has the technical potential to disrupt this negative cycle, the current dysfunction and bankruptcy of distribution companies starves the sector of revenue while representing a daunting renewal challenge in terms of customer trust, workforce, required civil works, and workplace culture. This shifts the fourth activity of designing distribution grids towards replacement and reinforcement. Furthermore, it makes paramount the fifth planning activity of re-establishing the environment where plans can actually be implemented.

When a power sector has arrived at a state of grid tension and poor service, it becomes common for all customers of all tiers to operate their own generation units purchased on the market. For a factory or large hotel, the prospect of offering electricity to neighbours is too great an investment of capital and effort in addition to their regular business activity, so the capacity factor of these investments remains low and no grid extension from these sources occurs. As a result, the economies of scale that are typical of the power sector are not realised and the systems become increasingly expensive and inefficient.

5.4 Renewables

The first consideration when planning the integration of renewable resources into an existing national power system is how their cost compares with other alternatives. As we have highlighted, the cost of renewable energy has experienced dramatic reductions, and SSA enjoys some of the most plentiful solar resource (Kemeny *et al.* 2014). However, the cost of renewables in SSA is higher than in developed countries as it needs to incorporate foreign exchange, payment, policy, and grid availability risk components.

Renewable energy can offer some particular advantages to electricity supply planners. For example, the implementation of many small and distributed projects connected to the distribution grid could serve as a back-up to centralised generation or reduce final demand. But as we have anticipated in a previous section, variable renewables can also bring challenges to the stability of the grid. One way of mitigating this is by building renewable power plants incrementally so that the new behaviour of the system can be observed and accommodated by operators. This is particularly relevant for the small systems of most SSA countries, where the share of renewables in the generation mix could increase substantially by adding relatively small plants.

A final consideration refers to the technical capability of renewable power plants to help maintain the voltage and frequency of the transmission system. Grid operators, planners and renewable energy developers need a fluent dialogue to adjust the technical parameters of renewables as well as to update the rules and regulations of a given

transmission system to take these into account. The training and analysis tools of transmission company staff to engage in such activities is seldom adequate, and this requires extra attention in developing countries to the fifth planning activity of ensuring and enabling the right environment.

6 The off-grid path

The off-grid path to electrification has typically not been considered in traditional electricity supply planning. However, the five planning activities previously discussed also apply in the context of off-grid electricity service (Trotter *et al.* 2017). Unlike traditional grid extension, off-grid electrification in Africa has been primarily a bottom-up, market-driven, decentralised phenomenon. The planning for off-grid electrification is informal and *ad hoc* with different actors, techno-economic realities, and service expectations. Renewable energy plays a crucial role in most off-grid electrification approaches.

6.1 Actors

In SSA, much more so than in developed countries, individual households and businesses are engaged in their own electricity supply planning. They do this by acquiring small-scale generator sets, dry cell batteries, solar lanterns, solar home systems, or by subscribing to an electricity service provided by a mini-grid.

Off-grid system manufacturers and distributors also act as planners. There are over 100 companies involved in the off-grid electricity access space (Bloomberg New Energy Finance and Lighting Global 2016). By offering products – solar lanterns and solar home systems – with specific capabilities, manufacturers are implicitly engaged in the demand estimation and generation technology selection activities of electricity service planning. The customer participates in these activities by acquiring certain products based upon their needs, preferences, and ability to pay. Whereas planning for on-grid electricity service involves determining which regions to serve through new electrical connections, an off-grid system distributor performs an analogous activity by choosing which geographic markets to enter.

Governments are not entirely divorced from planning aspects of off-grid electricity supply, however. Some REAs are engaged in the planning of off-grid systems – particularly larger scale mini-grids and in some instances solar home systems and lanterns (Bhattacharyya 2013; IEA and World Bank 2015; Tenenbaum *et al.* 2014). Governments can also contribute to an enabling environment for off-grid access by: setting quality standards for off-grid products, licensing and regulating companies across the value chain – including importers, suppliers, and installers – and setting tariff caps and subsidies (Smith *et al.* 2010).

6.2 Quality of service

The quality of service requirements for electricity in rural off-grid settings has been shown to be different from urban settings connected to the grid. This can be better understood by considering the main drivers for household electricity demand in rural areas.

The first driver is the proliferation and ubiquity of mobile phones. The mobile phone subscription rate in SSA is surprisingly high – estimated to be 76 subscriptions per 100 people (Louie *et al.* 2015). Mobile phones are extremely beneficial to villagers, allowing farmers to check market prices before selling, simplifying logistics, or enabling mobile payment (Louie and Dauenhauer 2016). Even in areas without reliable mobile service, mobile phones are popular as they can often be used as radios or to play music (Kemeny *et al.* 2014). Recharging the phones can require travel to the nearest electrified town, which could be many kilometres away (Adkins, Oppelstrup and Modi 2012).

The second main driver is lighting. In many areas, kerosene has been the fuel of choice for evening lighting. However, kerosene lamps have low efficacy and are linked with negative health and safety outcomes (Energy Sector Management Assistance Program 2015; Louie and Dauenhauer 2016). Kerosene lamps are often used indoors, where they might spill, or come in contact with flammable materials. Studies have shown an increased risk of cancer, respiratory infection, asthma, tuberculosis, and cataracts associated with kerosene use (Lam *et al.* 2012).

Mobile phone charging and electric lighting require only modest amounts of power and energy – typically less than 50W and less than 10KWh per year. Consequently, the electricity supply can be modestly sized, with limited availability – a few hours per day following sunset – and be deemed acceptable.

The reliability and adequacy requirements can also be low due to fuel stacking. Fuel stacking is the use of multiple energy sources to meet the same energy need (Energy Sector Management Assistance Program 2015). For example, households with electricity service might use an electric stove as well as charcoal for cooking. Fuel stacking builds in redundancy to the energy mix so that an electricity supply with low reliability and adequacy can be more easily tolerated.

Estimating demand for off-grid users is a particularly challenging and error-prone planning activity (Blodgett *et al.* 2017). The state-of-practice demand prediction for larger size systems like mini-grids is to utilise door-to-door surveys to gather information on actual and aspirational appliance ownership and usage, from which the demand is predicted. The predictions can be largely inaccurate (Louie and Dauenhauer 2016), which can lead to over- or under-designed systems. Over-designed grids are an inefficient use of capital, as money is wasted on excessively sized equipment, and the surplus energy cannot be sold elsewhere as can be done in an interconnected grid. Under-designed mini-grids are unreliable due to either power or energy limitations, but solar PV-based mini-grids benefit from modularity and can grow as demand grows.

6.3 Economic and social goals

The economic viability of off-grid systems is based on the premise that off-grid customers are willing and capable of paying a premium for

electricity. A business recharging mobile phones, for example, is often able to collect a fee ranging from 10 US cents to 50 US cents per charge. Given the small capacity of mobile phone batteries, this is approximately equivalent to US\$50/KWh – roughly 500 times the rate that is charged in the US. In addition, this sum is not insignificant to the rural villager who might average US\$3 per day in income. Non-electric lighting is also expensive, with 80 per cent of household fuel expenditures related to kerosene or candles reported in some areas (Adkins *et al.* 2012).

As a simple example, a US\$400 solar home system with a 100W panel optimistically can supply 500Wh per day, or 182.5KWh per year. That same consumption would cost a grid-connected customer US\$12.78 per year at a moderately subsidised rate of 7 US cents/KWh. Under these same rates, the solar home system would need to last 31 years for the investment to pay off, far longer than can be realistically expected. The spread of solar home systems is a testament to the high cost of energy experienced in rural areas. Electricity rates paid by the smallest customers of a for-profit mini-grid typically are in the range of US\$1 to US\$5/KWh. Selecting a rate that balances ability to pay with financial sustainability is important in mini-grid planning. Since many customers lack a credit profile, investing in a connection to house or business is financially risky. Collection of payment for energy consumption can be managed under pre-pay schemes in which a customer purchases units of energy, and their access is disabled once these units are consumed (Smith *et al.* 2010; Roach and Cohen n.d.).

Despite consideration of all of these factors, the financial sustainability of a mini-grid can be tenuous. Scaling up can improve financial performance for developers, but requires de-risking to attract external funding. Wider availability of business and performance data, along with best practices, can contribute to de-risk these investments.

6.4 Renewables

Renewable energy is central to off-grid electrification strategies. They are considered as the most economic off-grid electricity solution (IRENA 2015) because delivering petrol or diesel to rural and remote sites can triple their cost. However, systems with high-reliability requirements or those dependent on weather-driven renewable resources require some form of battery energy storage (typically lead-acid or lithium ion batteries), which can significantly add to their cost (Mandelli *et al.* 2016). The disposal of these batteries at the end of their life introduces additional logistical challenges, and can lead to serious environmental problems if it is not managed properly (Bensch, Peters and Sievert 2017).

7 Differentiated strengths: synthesis and conclusions

Historically, electricity access was conceptualised as a binary indicator – a home or business had access to the electrical grid, or they did not. This is the situation presumed in traditional planning methods. More recently, electricity access has come to be viewed along a quality-of-service

continuum, regardless of source, that acknowledges the different use-cases and realities of users. On one end of the continuum is a user with few resources and a limited ability to pay for electricity. Their electricity need is modest – basic night lighting and perhaps recharging a mobile phone. There are also customers that are grid-connected, which allows them to use appliances such as televisions and air conditioning but the supply is unreliable and of low quality; other users such as businesses require high-quality, high-reliability electricity, and have the means to pay for a grid connection and back-up generators and batteries. On the far end of the continuum is an industrial user who may require as much energy as many of the other types of customers, and require either a high-voltage grid connection or their own power plant. Energy system planning practice in SSA must find solutions to support the development of all these tiers of users, without the benefit of strong government surpluses.

In this article, we have discussed two potential pathways for electrification in SSA: grid extension and off-grid systems. The choice of one or the other, or both in different geographies depends on the desired tier of access, their economic viability, and the new opportunities brought by technological progress. Although grid coverage has traditionally been seen as the endpoint for all electrification paths, experience has shown that insisting on grid extension can lead to overextended systems providing poor service. Off-grid systems could be a temporary salve that allows economic growth to the level where payment to a centralised system is viable. Such an approach was followed in the Chinese rural electrification model. However, the African model might provide a different role for off-grid systems, where they are sufficient for economic growth and increasing access to higher energy tiers. Under this scenario, non-industrial value-creation activities would lower the energy intensity of the economy while cheaper energy storage would improve the performance of mini-grids. In this case, the off-grid renewables model could eventually support grid extension from energy hubs, which themselves derive only limited trading and reliability advantages from the national transmission grid.

State-led and market-led approaches can coexist in SSA for the provision of electricity through the previous pathways (Byrne *et al.* 2014). In any case, the review of previous electrification experiences has shown little precedent for rural electrification by market forces alone. Rather, strong government support – financially, politically, and regulatory – were essential to achieve universal access in countries like China or the US. Low ability to pay for electricity in rural areas of SSA also implies that subsidisation will be an essential component for universality. However, the state must ensure the viability of these subsidies for the power sector as a whole to avoid the financial collapse of electric utilities, a common feature in the African power sector. As developed countries look towards uncertain future scenarios and changing business models for utilities, they will stand to learn much from the discoveries of SSA practitioners of energy planning.

Notes

- 1 Capacity factor is the ratio of actual energy produced by an energy-generating unit or system in a given period, to the hypothetical maximum possible (i.e. energy produced from continuous operation at full rated power). Open Energy Information <https://openei.org>.
- 2 All countries compared for 'Energy > Electricity > Installed generating capacity per thousand people', *CIA World Factbooks* 2010, 2011, 2012, 2013. Population figures from World Bank: (1) United Nations Population Division, *World Population Prospects*, (2) United Nations Statistical Division, *Population and Vital Statistics Report* (various years), (3) Census reports and other statistical publications from national statistical offices, (4) Eurostat: *Demographic Statistics*, (5) Secretariat of the Pacific Community: *Statistics and Demography Programme*, and (6) US Census Bureau: *International Database*. Aggregates compiled by NationMaster. Retrieved from www.nationmaster.com/country-info/stats/Energy/Electricity/Installed-generating-capacity-per-thousand-people.
- 3 Power, measured in watts (W), is the flow of energy over a unit of time. Some appliances have high power requirements, for example an iron, whereas others have low power requirements, for example an LED bulb.
- 4 Energy, measured in watt hours (Wh) is the product of power and time. Power and energy are analogous to speed and distance; speed refers to the rate of travel, whereas power refers to the rate of energy consumption.

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